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NASA Project Apollo Working Paper No. 1036

PROJECT APOLLO

CONSIDERATION TOWARD DESIGN

OF A

SPACE RADIATOR FOR APOLLO

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

Langley Air Force Base, Va.

December 29, 1961

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SPACE RADIATOR FOR APOLLO

Prepared by: Walter W. Guy

Walter W. Guy
AST, Flight Systems

Authorized for Distribution:

Robert R. Gilruth

Robert R. Gilruth, Director

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SUMMARY

A study has been made to evaluate the effectiveness of a radiator system for thermal control of a spacecraft in earth orbit, deep space, lunar orbit, and on the lunar surface. This study concludes that: (1) heat rejection from an unassisted radiator system is feasible in either deep space or in earth orbit; (2) the lunar-orbit heat rejection will be a problem of transient conditions, dependent on the time constant of the thermal-rejection system for successful operation; (3) unless shields are employed or the landing site selected such that the maximum heat load will not occur, the unassisted radiator system will not function adequately over all portions of the lunar surface.

INTRODUCTION

The design of a heat-rejection system for effective operation is dependent on a competent analysis and evaluation of the environment in which it will be required to function. As a design criteria, maximum heat-rate conditions were assumed. This steady-state analysis was necessary prior to a more detailed cooling-system component design in which materials, configuration, and construction are important factors in order to insure the thermal loading imposed on the system would not exceed its capabilities.

For this study, several practical assumptions were made as follows:

(a) Solar constant = 440 Btu/ft^2hr

(b) Lunar albedo = 0.07

(c) Earth albedo = 0.40

(d) Spacecraft radiator

(1) 100 percent efficient

(2) Circumferential

(3) Constant temperature

(4) Surface emissivity = 0.90

(5) Surface solar absorptivity = 0.15

(e) Earth orbit - altitude, 300 miles

(f) Lunar orbit - altitude, 50 miles

This study was conducted with the assistance of the NASA Manned Spacecraft Center Heat Transfer Section.

The selection of an emissivity of 0.90 appears reasonable. For titanium oxide, emissivity = 0.95, and for magnesium oxide, emissivity = 0.90. The absorptivity of titanium oxide is 0.18 and magnesium oxide is 0.08. The selected absorptivity of 0.15 is a conservative compromise.

With sufficient coolant flow, the radiator temperature can be equalized to eliminate areas of high temperature due to the solar flux or lunar and earth reradiation and albedos (reflection).

MISSION PROFILE

An evaluation of the effectiveness of the radiator system of a spacecraft in four different environments has been made.

Earth-Orbit Conditions

For the earth orbit, a maximum albedo of 176 Btu/ft^{2}hr and an average infrared radiation of 66 Btu/ft^{2}hr were used. Because of the 24-hour rotational period of the earth, and the relatively small difference in surface temperatures from day to night, this assumption is reasonable. The solar energy absorbed cannot be averaged because it varies from a maximum of 440 Btu/ft^{2}hr on the day side at the subsolar point to zero for the night side of the earth. The maximum value was used for this condition. The spacecraft orientation was with the center line of the craft perpendicular to a line connecting the earth and the sun.

Deep-Space Conditions

The deep-space analysis considers solar radiation of 440 Btu/ft^{2}hr as the only heat source. The spacecraft orientation for maximum heating rates is with the center line of the craft perpendicular to a line normal to the sun.

Lunar-Orbit Conditions

For lunar orbit, a maximum albedo of 30 Btu/ft^{2}hr and infrared radiation of 410 Btu/ft^{2}hr were used. Because of the 28-day rotational period of the moon and the wide difference in surface temperatures from day (710° R) to night (200° R), peak heating loads will occur that must be designed for. The solar energy absorbed was also considered as a maximum. The orientation of the spacecraft was again taken to obtain the maximum heating rates with the center line of the craft perpendicular to the line connecting the moon and the sun.

Lunar-Landing Conditions

For lunar landing, the maximum heat load was assumed with the spacecraft at the subsolar point at high noon on the equator. Lunar infrared was considered to be radiated in all directions, the lunar albedo was also considered to be reflected in all directions, and the intensity of both varied from the normal as the cosine of the angle. Both vertical and horizontal positions were considered at this maximum heating condition.

For a horizontal position of the spacecraft at the subsolar point, an alternate radiator configuration was evaluated, using only a part of the cylindrical surface area of the vehicle for heat rejection.

RESULTS

The internal heat load of Apollo is approximately 8,500 Btu/hr. The metabolic heat, 1,500 Btu/hr, LiOH heat of absorption, 200 Btu/hr, and for the purpose of this paper an assumed value of about 20 percent of the electrical heat load, 1,300 Btu/hr, will be introduced to the cabin atmosphere. This 3,000 Btu/hr must be rejected from the cabin at approximately 40° F. The remainder of the electrical load, 5,500 Btu/hr, can be rejected at temperatures up to 120° F.

Radiators of less than 125 square feet surface area are compatible with the present Apollo configuration.

Earth Orbit.- Figure 1 shows the net heat rejection from a radiator at temperatures from 40° F to 160° F in the earth-orbit environmental condition. As seen in this figure, the radiators will function effectively throughout the temperature range considered. The dissipation of 3,000 Btu/hr at 40° F can be accomplished with 55 square feet of radiator surface. 42 square feet of surface are required to reject 5,500 Btu/hr at 120° F.

Deep Space. - The deep-space heat rejection is shown as a function of radiator area at various radiator temperatures in figure 2. This graph indicates that thermal dissipation can be successfully accomplished within the temperature range of 40° F to 160° F. The thermal rejection of 3,000 Btu/hr at 40° F and 5,500 Btu/hr at 120° F will require 40 square feet and 36 square feet respectively.

Lunar Orbit. - Figure 3 depicts the heat rejection during lunar orbit from a radiator at various temperatures. The 5,500 Btu/hr to be rejected at 120° F will require 120 square feet of radiator surface. Under the maximum conditions imposed, a radiator of lower than 80° F temperature will not dissipate thermal energy. Due to the orbital nature of the mission, the thermal rejection will become a transient problem. The external heat load will fluctuate from the maximum condition, as considered, to a minimum when the spacecraft is traveling in the shadow of the moon. While in the shadow, the only heat absorbed by the spacecraft is radiated as infrared from the -260° F lunar surface. Because of the low heat flux environment, the thermal rejection capacity of the radiator system will be increased. By precooling the crew compartment during the shadow side of the orbit, the problem of low-temperature radiator ineffectiveness at peak heating may be minimized.

Lunar Surface (Vertical Position). - The net heat rejected on the lunar surface at the subsolar point for various radiator temperatures is shown in figure 4. The broken line in figure 4 represents the net heat transfer available for a 160° F radiator. Radiator temperatures much below this value are unfeasible at the position and conditions assumed unless the radiator is shielded from the lunar surface. The efficiency of this shielding is dependent on its configuration, emissivity and solar absorptivity. As a design criteria, a 100 percent effective configuration for the shield and realistic emissivities and absorptivities were used. The shield was considered circumferential, perpendicular to the radiator and of infinite diameter. This configuration eliminates all direct radiation interchange between the radiator and the lunar surface. An emissivity of 0.1 and a solar absorptivity of 0.3 were assumed (for aluminized surfaces, emissivities of 0.05 and absorptivities of 0.26 are possible). The shielded radiator will reject the 3,000 Btu/hr at 40° F with 45 square feet of surface area and 5,500 Btu/hr at 120° F with 38 square feet.

Figures 5 and 6 indicate the cabin heat load can be dissipated by 120 square feet of a 40° F unshielded radiator at 6 days from the subsolar point. An increased radiator effectiveness is realized if the spacecraft is farther than 6 days from high noon and a decreased effectiveness if the spacecraft is closer. These figures also show effectiveness can be maintained in the 120° F unshielded radiator to within approximately $4\frac{1}{2}$ days. This effectiveness also increases with distance from the subsolar point. Surplus water available at touchdown (ref. 1) could be utilized for supplemental cooling.

Figure 7 relates radiator surface area to length on the Apollo spacecraft for different radiator efficiencies. For example, a 100-square-foot radiator with an efficiency of 80 percent will require a length of 3 feet.

Lunar Surface (Horizontal Position).- Figures 8(a) to 8(f) indicate the gains made in total heat dissipation by decreasing the included angle of the radiative segment from 180° to 90° to improve the effectiveness of the high temperature radiators. This is summarized in figure 9 in which the heat rejection per unit area on the lunar surface at various radiator included angles (θ) is shown. This figure indicates that selection of the proper segment of the cylindrical surface of the vehicle for the radiator can increase specific thermal dissipation.

Figure 10 relates the radiating area to the available length on the Apollo spacecraft with a diameter of 156 inches. The combination of figure 10 with figures 8 and 9 results in figure 11. This figure depicts the total heat rejected as a function of the included angle on the Apollo spacecraft assuming a radiator length of 100 inches. This figure indicates that the 160° F radiator on the Apollo spacecraft reaches optimum performance at about 140° included angle. A size increase through enlarging the included angle, up to the 180° considered, has negligible effect on total heat rejected. The optimum total heat rejection value for the 120° F radiator is decreased considerably if the included angle is increased much beyond 120°. For the 80° radiator, an included angle more than 90° results in a reduction in total thermal dissipation.

CONCLUSIONS

This study indicates that an unassisted radiator system can reject the total heat load in earth orbit or deep space.

Only the higher temperature radiators will function properly at peak heating during the lunar orbit, the lower temperature radiators will depend on the system transients to meet the requirements. It is possible that the heat-sink capability of the spacecraft would offset the peak condition.

The cabin and electrical heat loads can be rejected by an unshielded radiator system in the vertical position on the lunar surface as long as the spacecraft is approximately 6 days from the subsolar point. Unless the spacecraft can touch down at some point other than near the subsolar point, shielding, supplemental cooling or refrigeration will be needed on the moon. Utilizing the available water for cabin heat load rejection, the remainder of the thermal dissipation could be accomplished by an unassisted radiator system to within 5 days of high noon. To reject heat closer to the subsolar point, a shield or refrigeration would become necessary. With sufficiently high shield effectiveness, a completely arbitrary landing site could be selected without regard to solar position. Without shields, mechanical heat rejection will become necessary.

With the alternate radiator configuration considered for the horizontal lunar landing condition, a saving in radiator size can be effected for a given heat load and radiating temperature by utilizing the optimum radiative segment.

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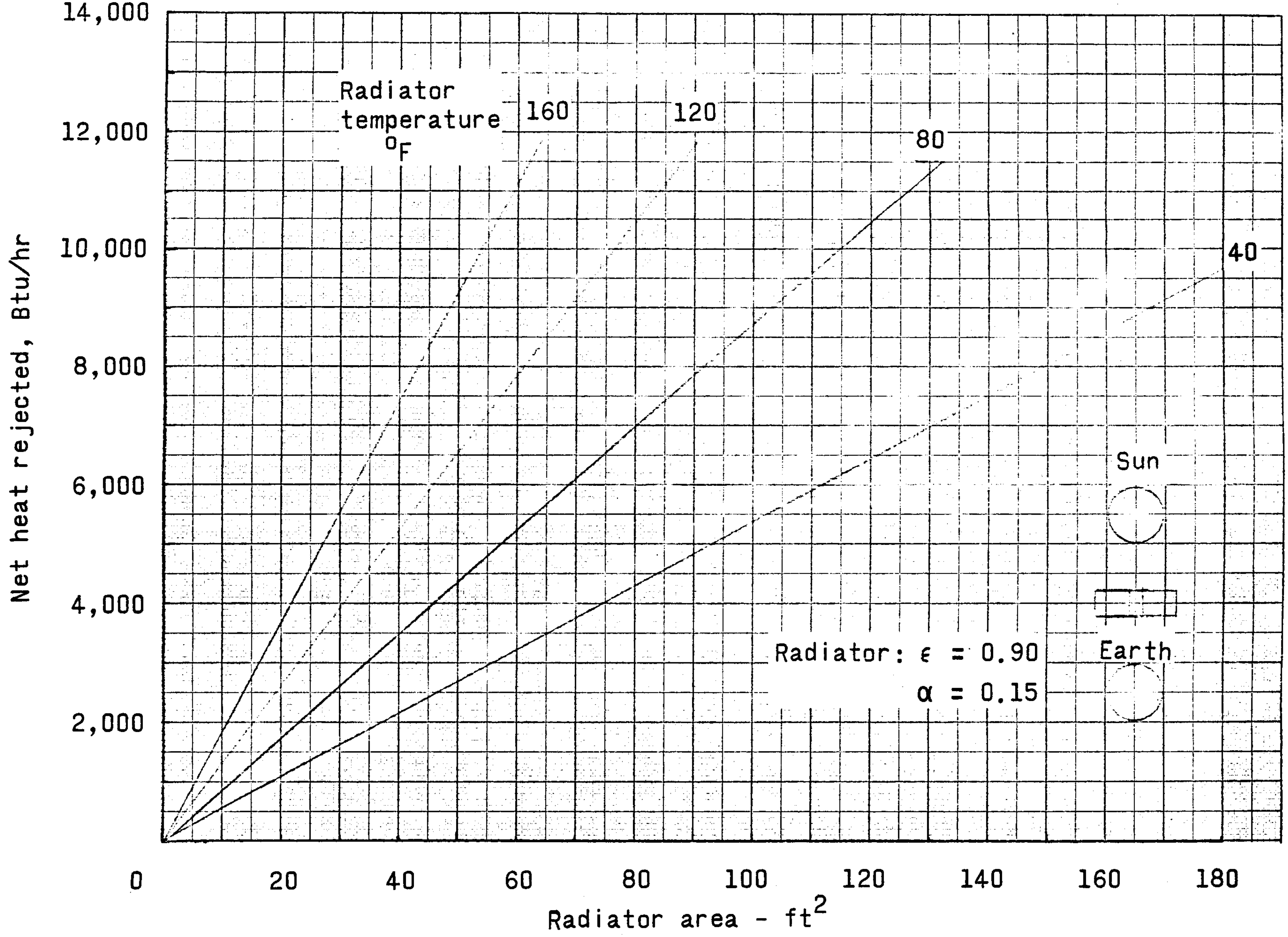


Figure 1.- Minimum net heat rejected in earth orbit.

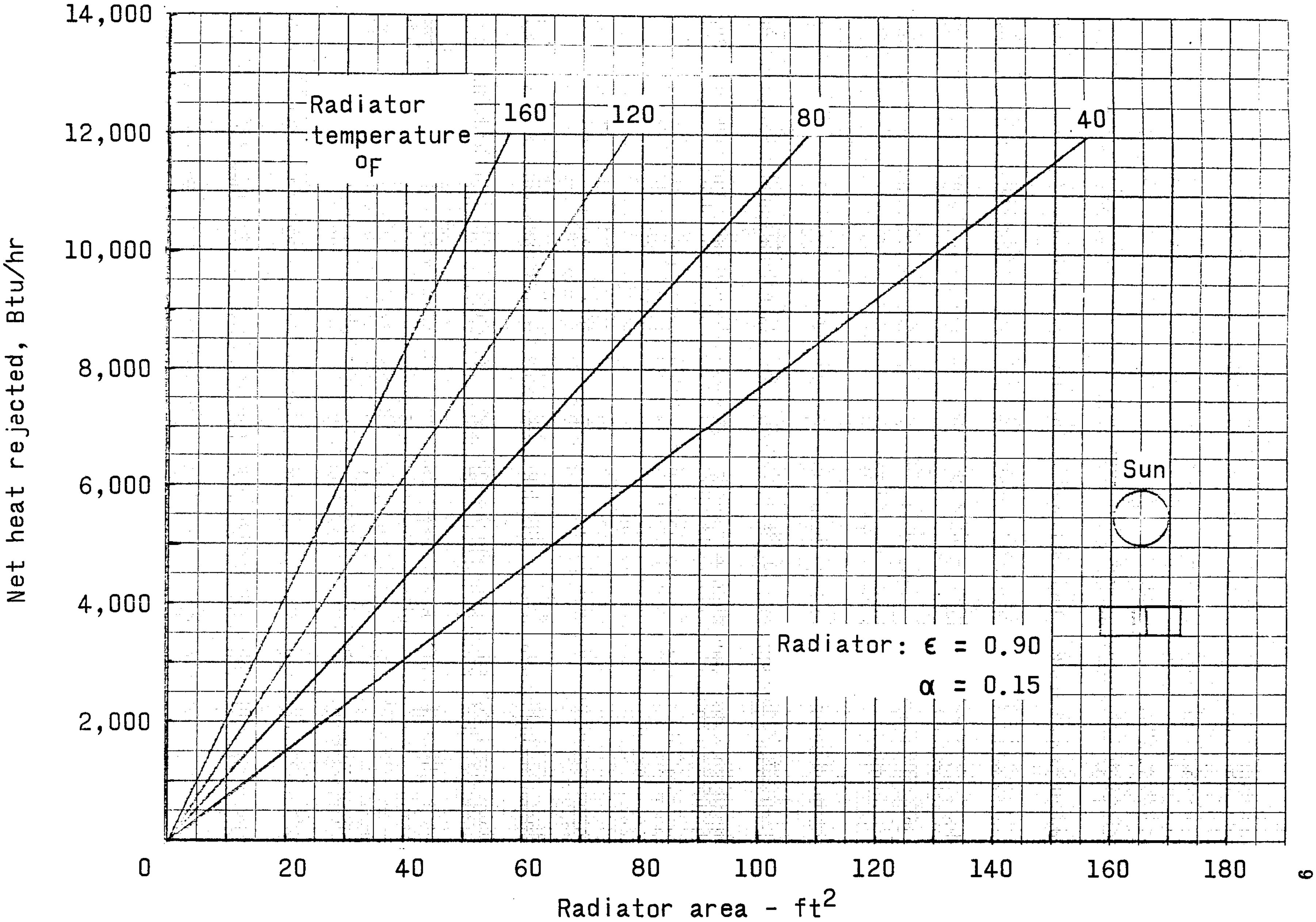


Figure 2.- Minimum net heat rejected in deep space.

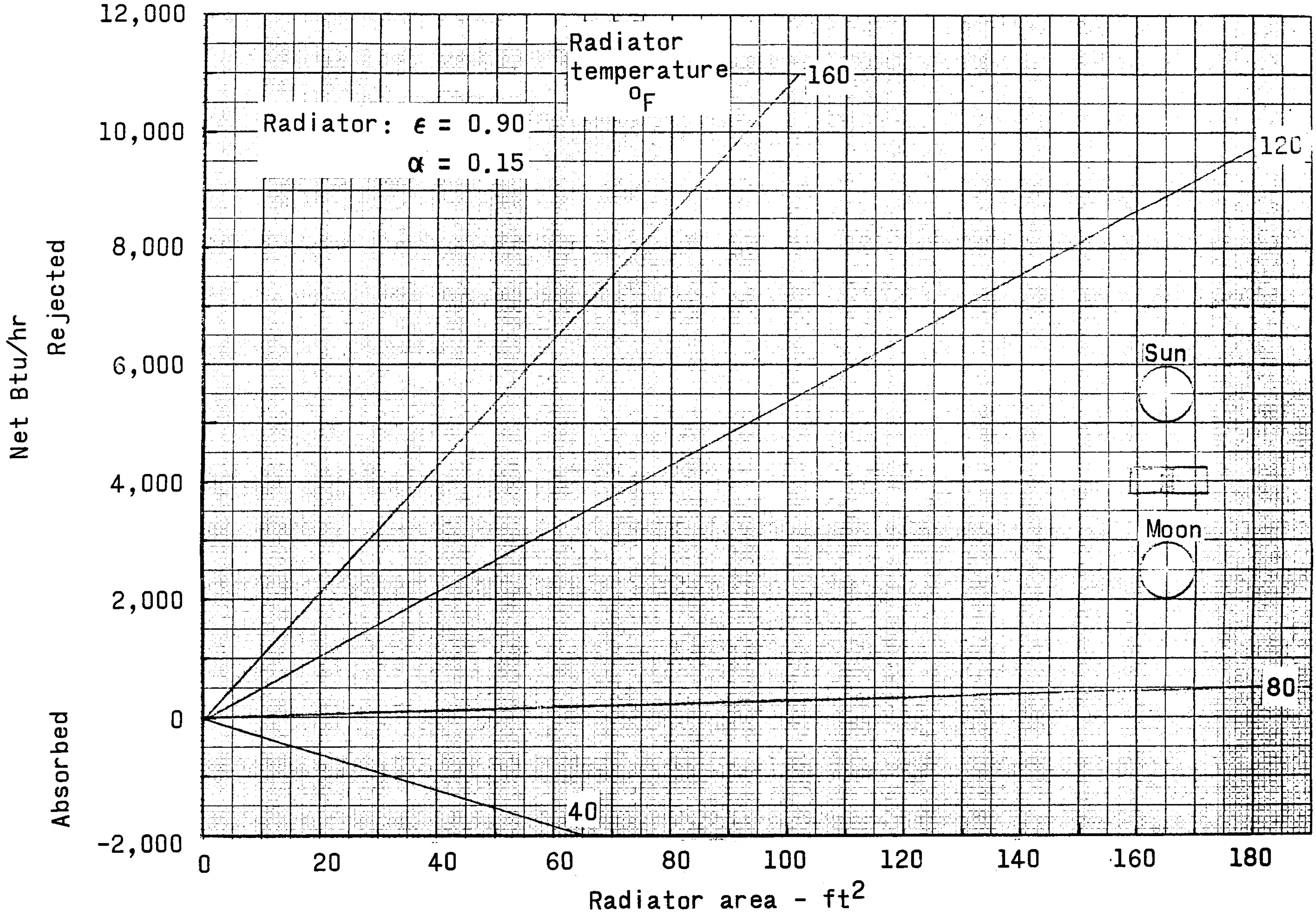


Figure 3.- Minimum net heat rejected in lunar orbit.

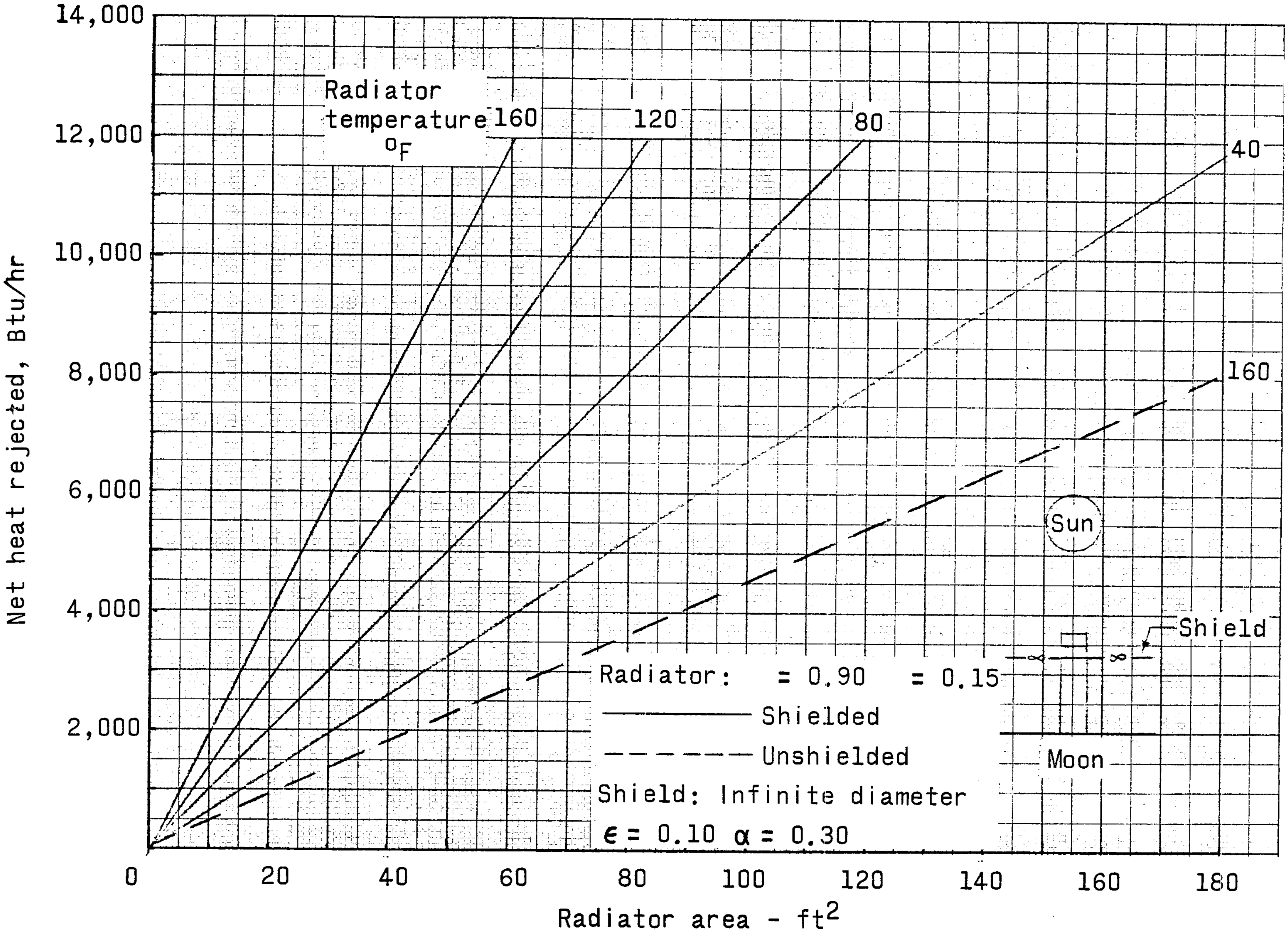


Figure 4.- Minimum heat rejected on moon's surface. Vertical landing.

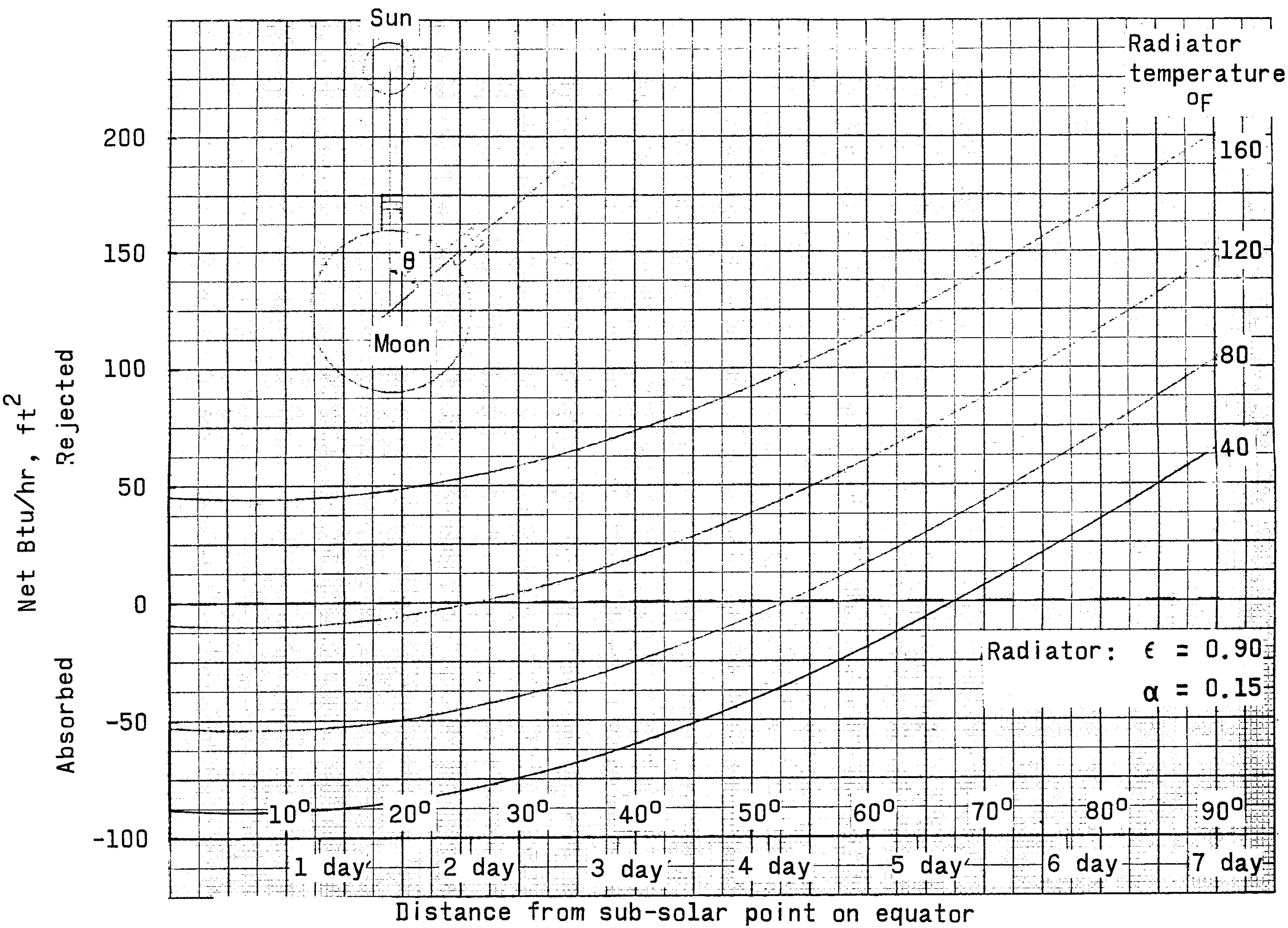


Figure 5.- Heat balance on lunar surface. (vertical position)

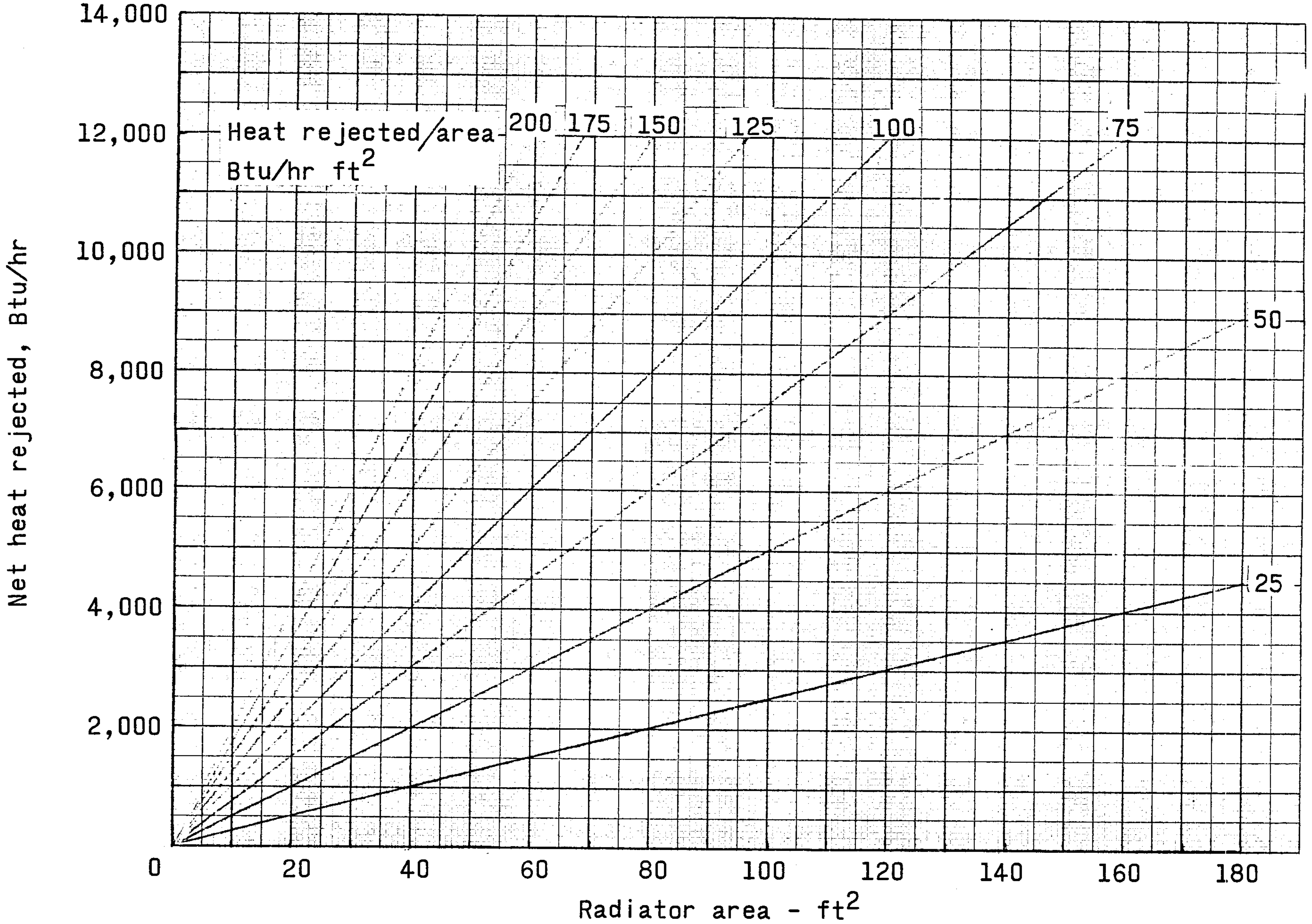


Figure 6.- Heat rejected versus radiator area.

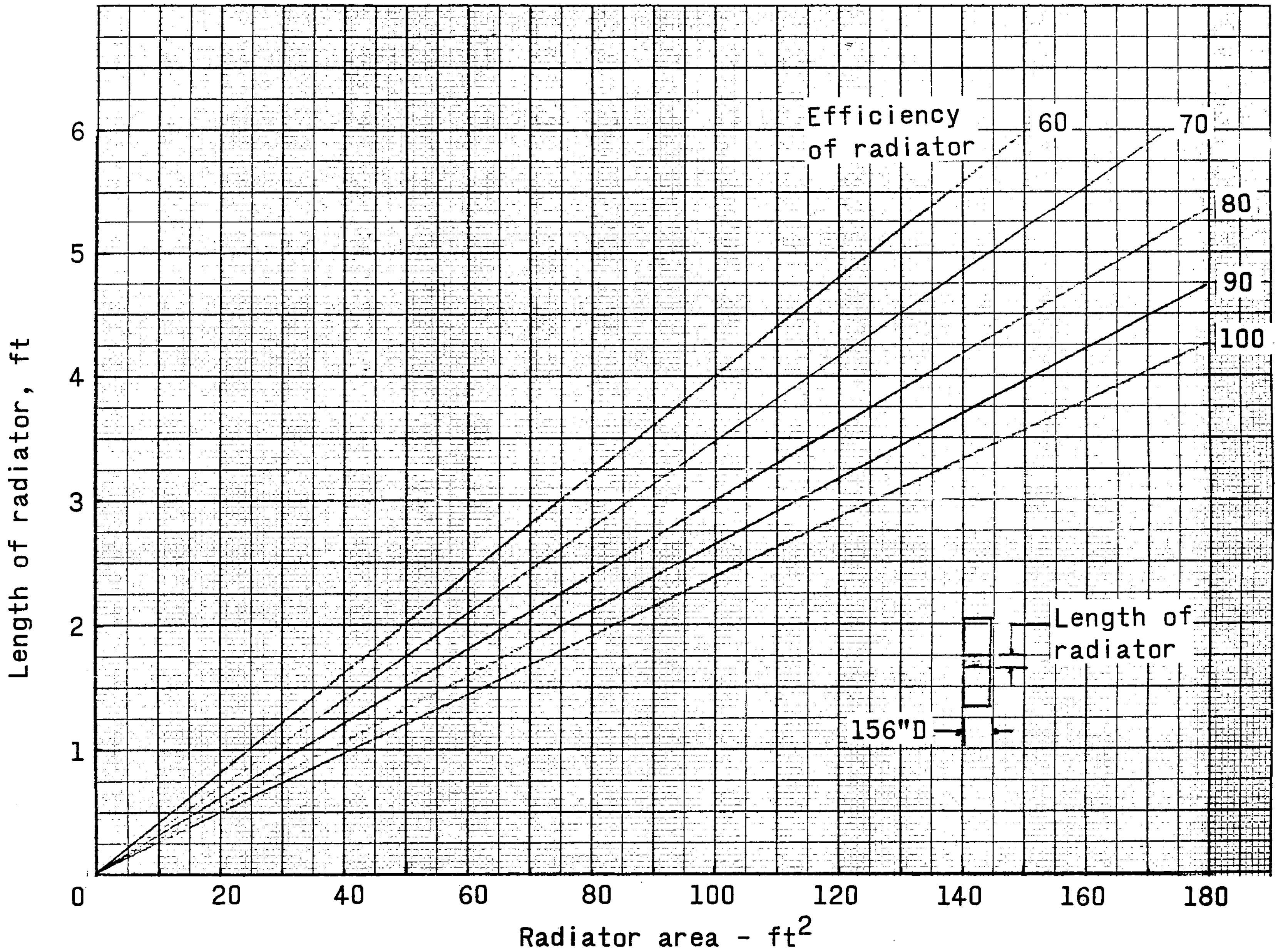
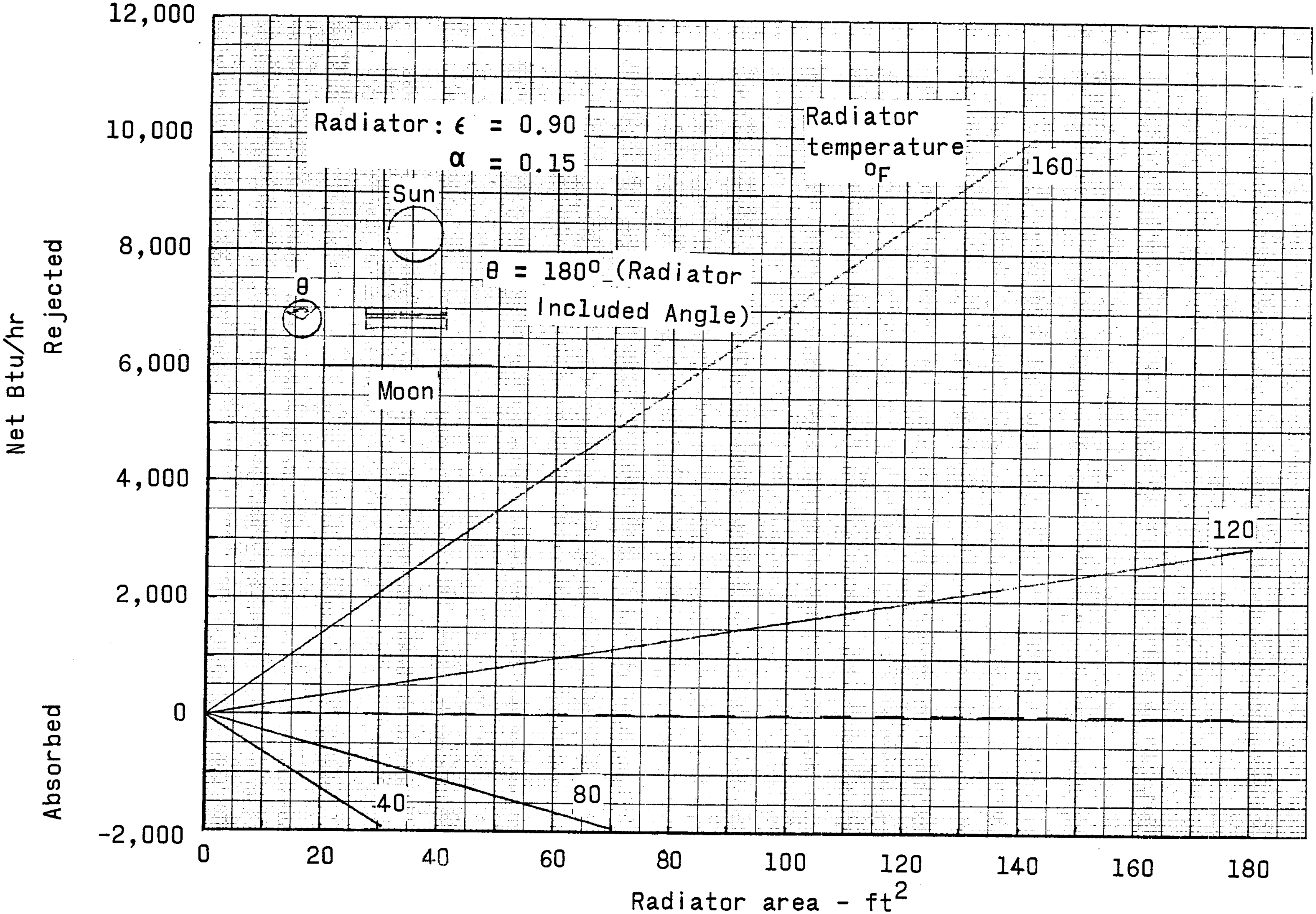
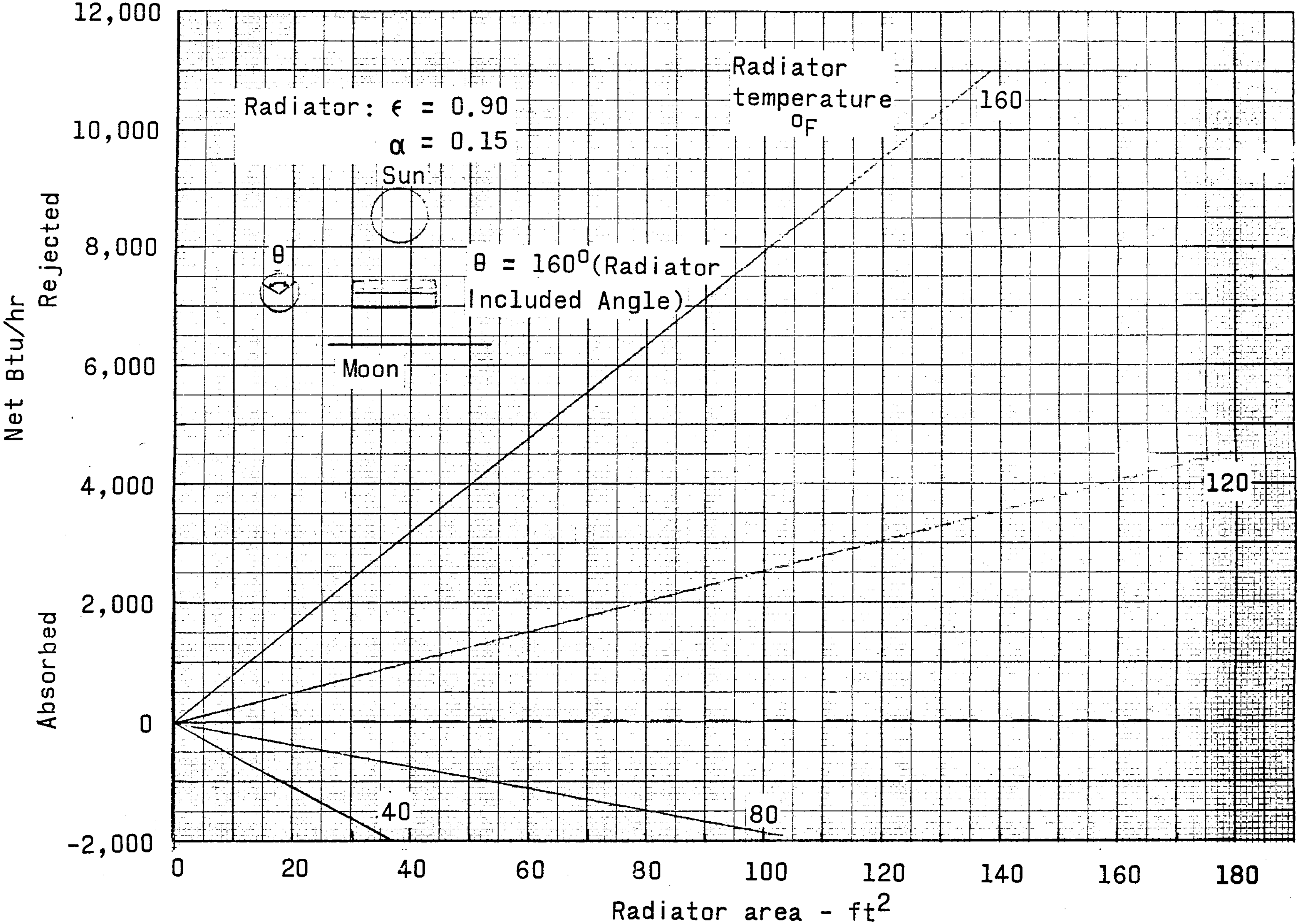


Figure 7.- Radiator size.



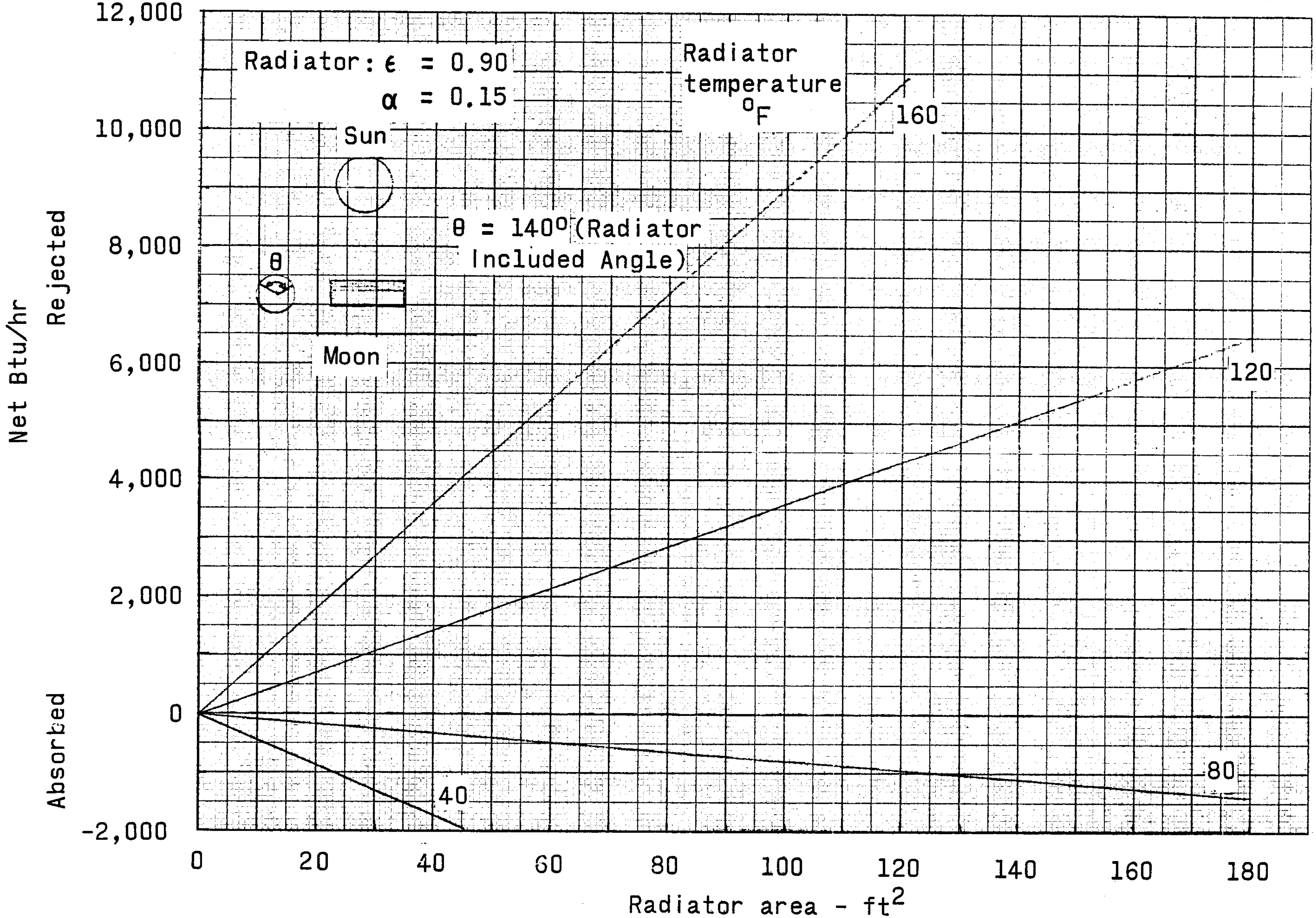
(a) $\theta = 180^{\circ}$.

Figure 8. - Heat rejection for horizontal lunar landing.



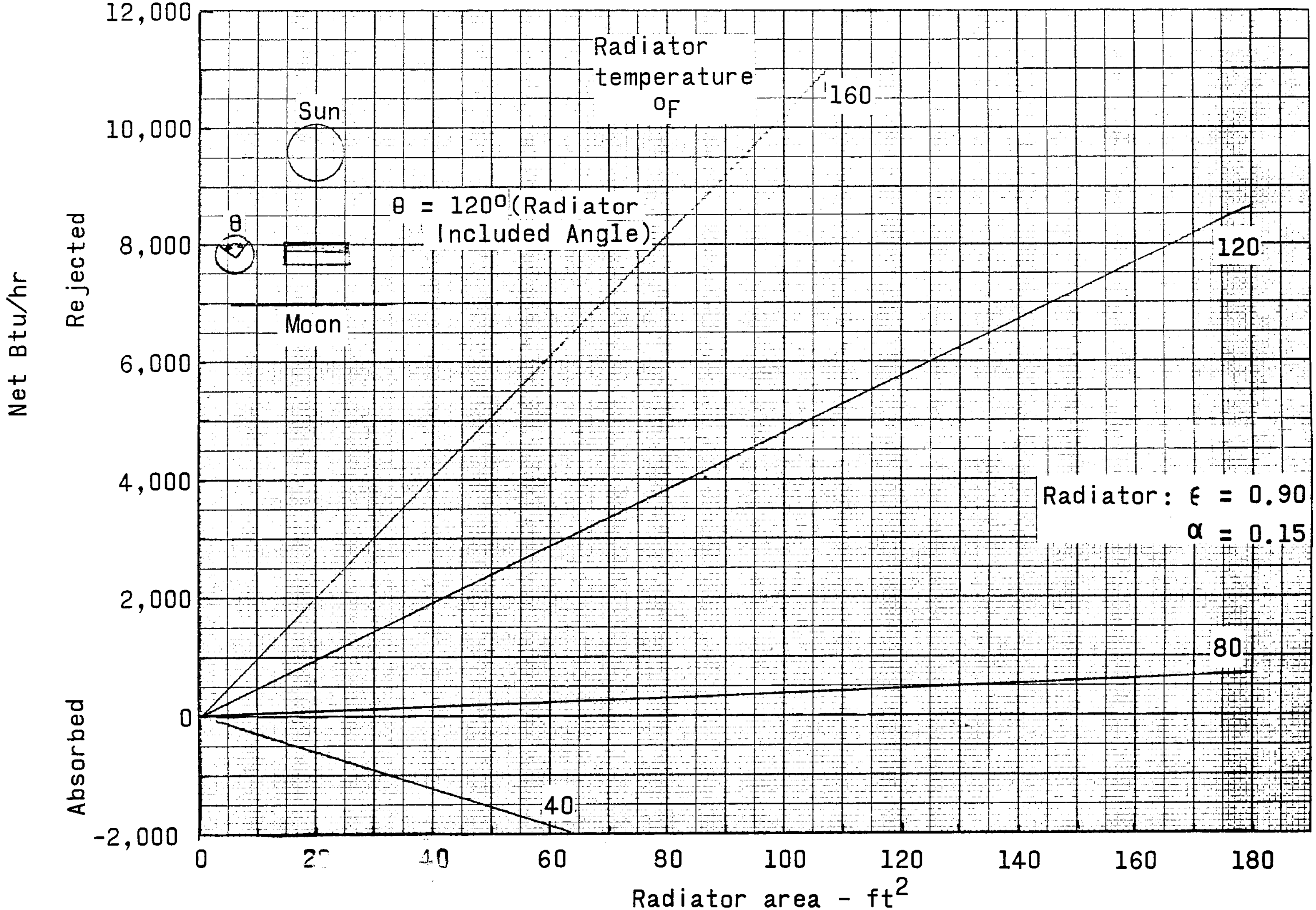
(b) θ = 160°.

Figure 8.- Continued.



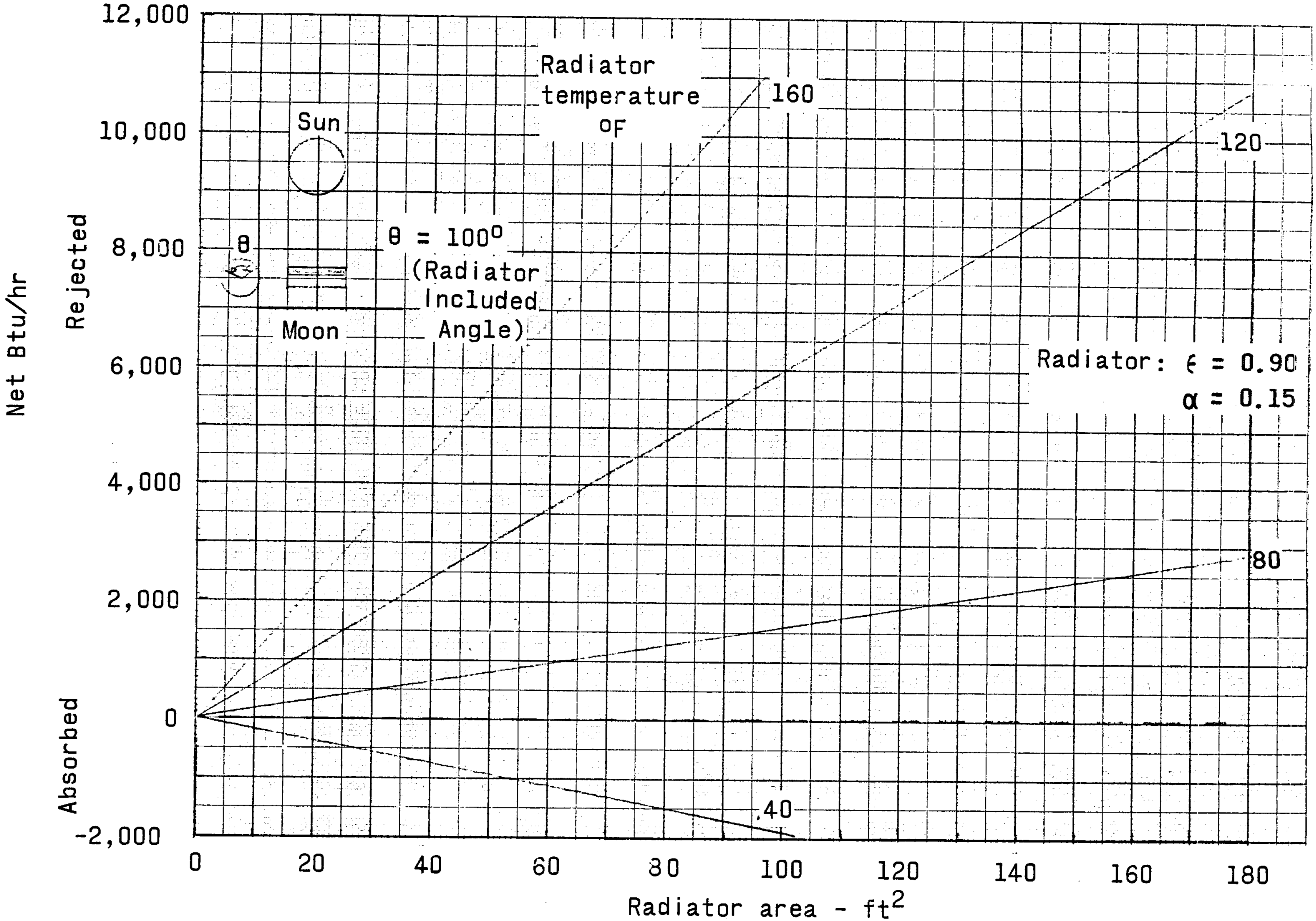
(c) $\theta = 140^{\circ}$.

Figure 8.- Continued.



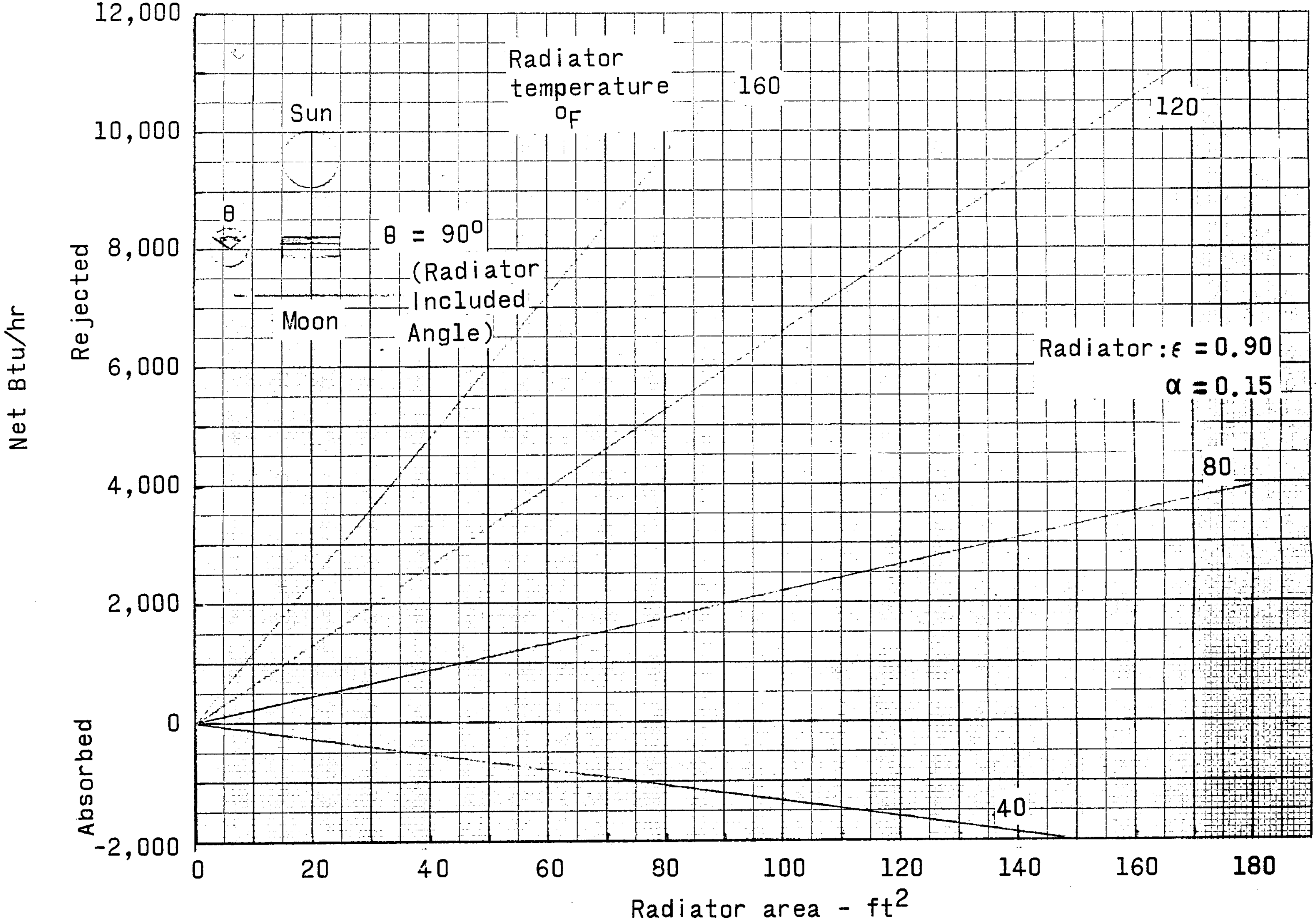
(d) $\theta = 120^{\circ}$.

Figure 8.- Continued.



(e) θ = 100°.

Figure 8.- Continued.



(f) $\theta = 90^{\circ}$.

Figure 8.- Concluded.

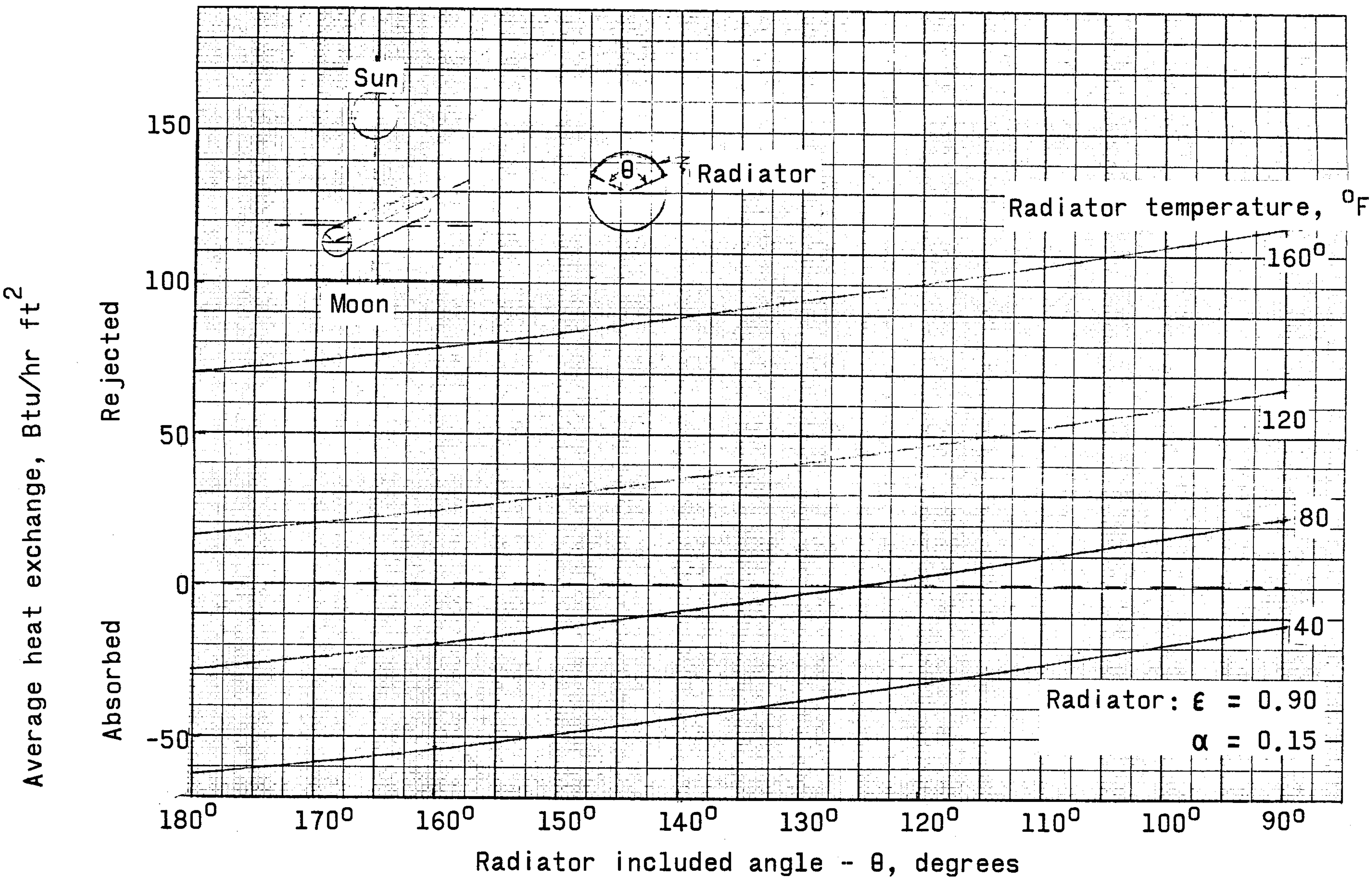


Figure 9.- Minimum heat rejected on lunar surface. Horizontal landing.

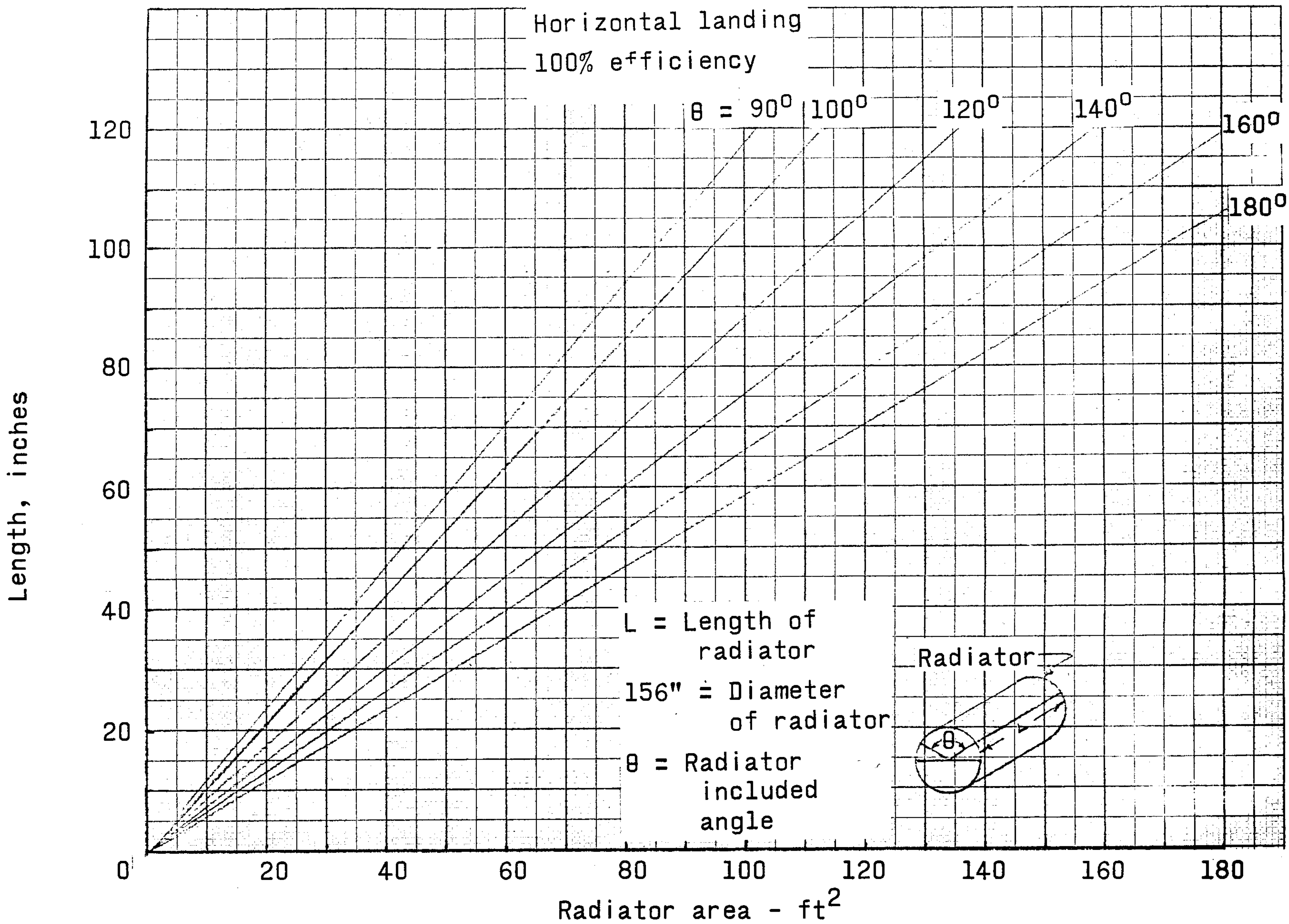


Figure 10.- Radiator size.

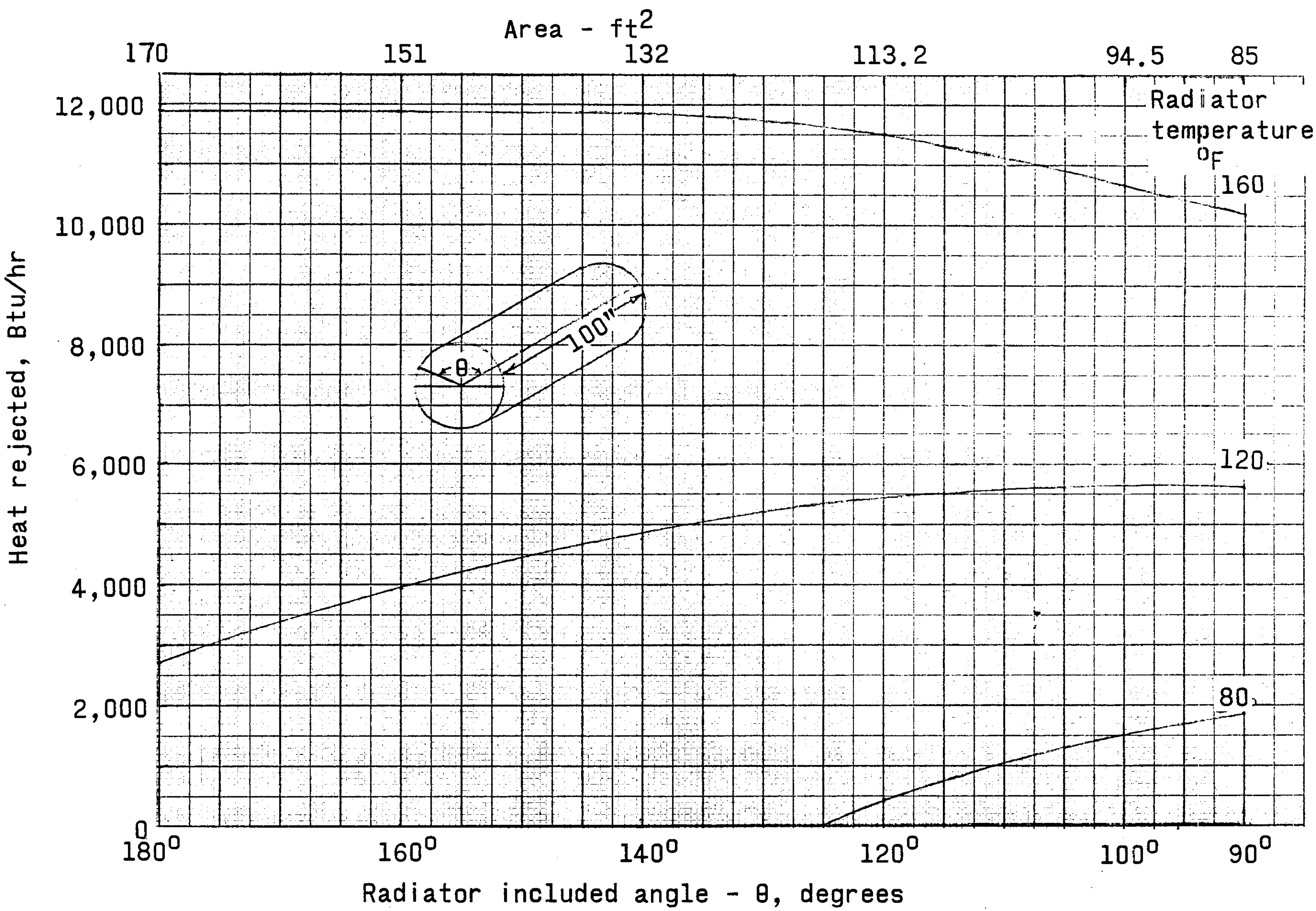


Figure 11.- Heat rejection on lunar surface for horizontal landing.